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Altered tuffaceous rocks of the Green River Formation in the Piceance Creek Basin, Colorado

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ALTERED TUFFACEOUS ROCKS OF THE GREEN RIVER FORMATION

IN THE PICEANCE CREEK BASIN, COLORADO

By Roy L. Griggs

ABSTRACT

More than 50 ash-fall tuff beds which have altered to analcitized or feldspathized rocks have been found in the upper 500-600 feet of the Parachute Creek Member of the Green River Formation in the Piceance Creek Basin of northwestern Colorado. Similarly altered water-washed tuff occurs as tongues in the uppermost part of this member, and forms most of the lower 400-600 feet of the overlying Evacuation Creek Member of the Green River Formation.

The altered ash-fall beds of the Parachute Creek Member are all thin and show a characteristic pattern of alteration. Most beds range in thickness from a fraction of an inch to a few inches. One bed reaches a maximum thickness of 5 feet, and, unlike the other beds, is composed of several successive ash falls. The pattern of alteration changes from the outer part to the center of the basin. Most beds in the outer part of the basin contain about 50 to 65 percent analcite, with the interstices between the crystals filled mainly by microlites of feldspar, opal, and quartz, and small amounts of carbonate. At the center of the basin essentially all the beds are composed of microlites of feldspar, opal, and quartz, and small amounts of carbonate.

The tongues of water-washed tuff in the uppermost part of the Parachute Creek Member and the similar rocks composing the lower 400-600 feet of the Evacuation Creek Member are feldspathized rocks composed mainly of microlites of feldspar, opal, and quartz, varying amounts of carbonate, and in some specimens tiny subrounded crystals of analcite.

The general trend in alteration of the tuffaceous rocks from analcitization near the margin to feldspathization near the center of the Piceance Creek Basin is believed to have taken place at shallow depth during diagenesis, as indicated by field observations and laboratory work. It is believed that during sedimentation and diagenesis the waters of the central part of the basin were more alkaline and that

following the breakdown of the original tuffaceous glass to a colloidal gel during diagenesis analcitized rocks crystallized near the basin margin and feldspathized rocks crystallized near the center of the basin.

INTRODUCTION

Historical summary

In the summer of 1925 W. H. Bradley (1928) found some analcite-bearing beds that resembled sandstone in the field, interbedded in the Green River Formation in Uintah County, Utah, and in Rio Blanco and Garfield Counties, Colo. Bradley noted that the thin beds contained analcite in varying amounts, some beds containing large amounts of euhedral crystals while others contained relatively little analcite. He also noted that the beds with relatively little analcite had a distinctly tuffaceous appearance, and a dominant matrix of chalcedony in which were "embedded many angular fragments and elongate splinters of feldspar and quartz together with laths of biotite and euhedral crystals of orthoclase, apatite, and zircon." Also noted in rare cases were crystals of plagioclase and hornblende or pyroxene. Bradley deduced from the gradation of beds composed largely of analcite crystals with a subordinate matrix to beds with a distinctly tuffaceous texture that these analcite-bearing rocks had originated from the alteration of volcanic ash and that the alteration had taken place "on the lake bottom (or when only shallowly buried in [the] ooze)" of the accumulating lake sediments which gave rise to the Green River Formation. In this brief though unusual paper it was predicted that careful tracing of the beds would show the existence of their great lateral extent, comparable to that of bentonite beds and therefore of probable future usefulness in correlation.

Later, Bradley (1929, p. 1-6) wrote a more comprehensive paper describing these analcite-bearing beds, and discussed further the alteration of the volcanic glass from which he believed the beds had formed. This longer paper contains a photomicrograph of an analcitized specimen with a distinctly tuffaceous appearance, and evidence was presented that the alteration probably took place at a temperature below 30°C and before individual beds were buried as much as 100 feet.

Twenty years later, Duncan and Denson (1949), while working on the geology of Naval Oil Shale Reserves 1 and 3 near Rifle, Colo., used four thin analcitized beds in the formation as stratigraphic markers. Still later, Cashion, Donnell, and coworkers (Donnell and others, 1953; Cashion and Brown, 1956; Cashion, 1959; Donnell, 1961) noticed that some of the analcite-bearing beds extended for considerable distances into the Piceance Creek Basin of Colorado and the Uinta Basin of Utah. Consequently, the beds became accepted unquestionably as altered ash falls because of their extent. Bradley's original deductions had been remarkable.

Purpose of this investigation

This study was made mainly to determine whether or not any of the altered tuff beds in the Piceance Creek Basin (fig. 1) had sufficiently distinctive petrographic or mineralogic characteristics such as the well-known Pearlette Ash Member to allow their use as stratigraphic markers throughout the regional extent of the important oil-shale-bearing Green River Formation in Colorado, Utah, and Wyoming. No single bed has been found which has such highly distinctive petrographic or mineralogic characteristics that it unquestionably can be recognized throughout the Piceance Creek Basin without some knowledge of its association with other beds, though one multiple ash-fall bed approaches easy recognition.

The study, however, even though essentially confined to one member of the formation, has yielded data on the general character and widespread stratigraphic distribution of tuffaceous material within the Green River Formation. In addition, the study has shown that in the central part of the area the original tuffaceous glass has altered mainly to feldspar and quartz instead of analcite-bearing rocks.

Area studied

The area studied for this report is the main part of the Piceance Creek Basin as described by Donnell (1961, p. 859). This basin "* * * is asymmetric, with very gently dipping limbs on the south and west and more steeply dipping limbs on the north and east. In the Green River Formation the dips range from as low as 0.5° on the south margin to as great as 27° on the north rim. * * * the axis of the basin at the surface roughly parallels the eastern margin of the area at a position about 10 to 15 miles from that margin." Within the Piceance Creek Basin in the area between the White and Colorado Rivers, the main part of the Green River Formation forms a high, northerly sloping plateau. In places this plateau rises more than 4,000 feet above the surrounding terrain, and the highest point on the south rim rises to an altitude of about 9,400 feet. The Green River Formation is exposed in generally white to light-gray cliffs around the rim of the plateau. This study was limited essentially to the rocks of this plateau.

The formation is about 5,000 feet thick near the center of the basin (D. C. Duncan, oral commun., 1964), and it has been subdivided into five members. These members are: the Douglas Creek, the Garden Gulch, the Anvil Points, the Parachute Creek, and the Evacuation Creek. For detailed descriptions of these members the reader is referred to Donnell (1961).

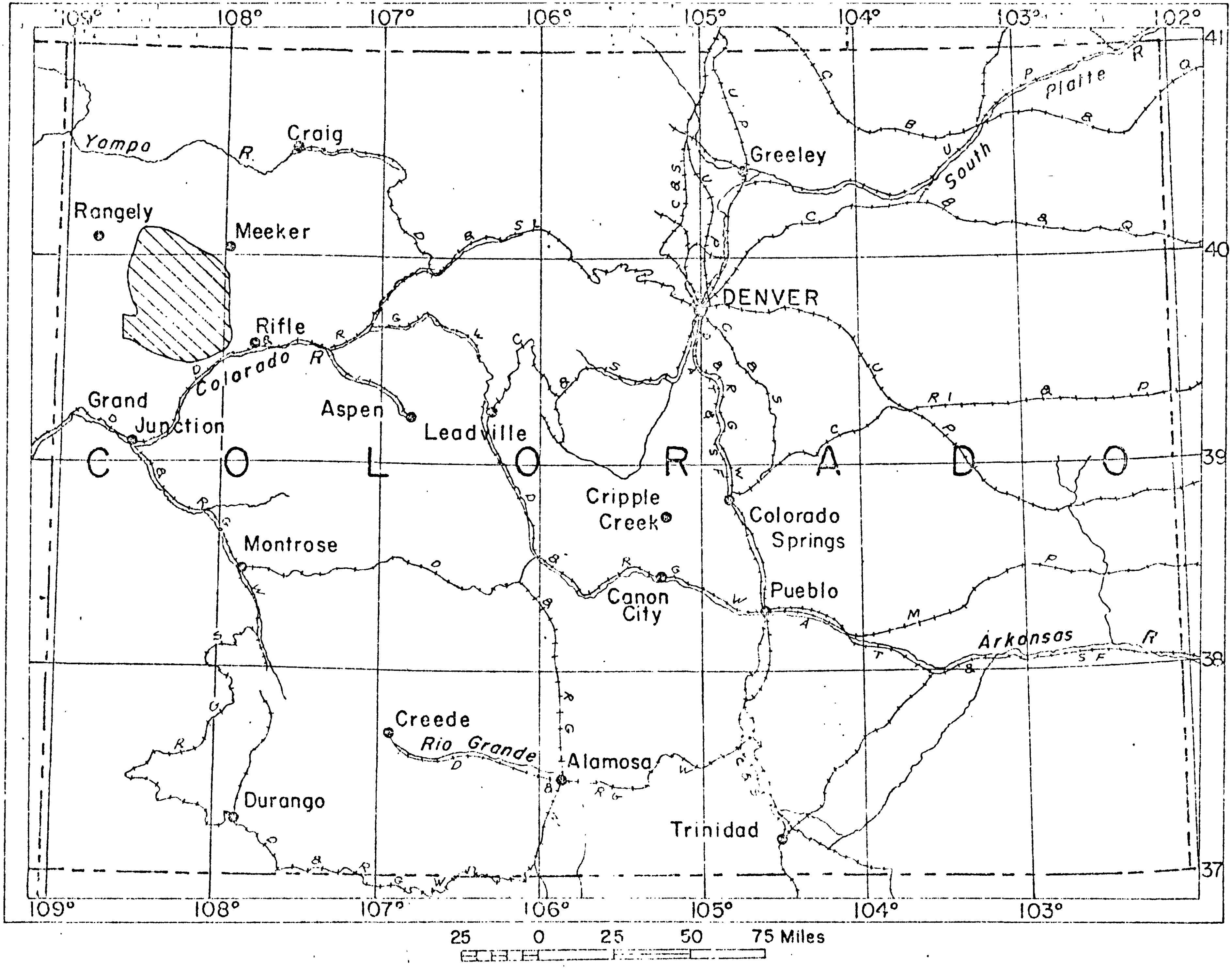

Figure 1.--Index map of Colorado showing location of Piceance Creek Basin (patterned).

Methods of investigation

This study consisted mainly of examining the altered ash-fall tuff beds and altered water-washed tuff of the Parachute Creek Member. Samples of such beds were collected from seven diamond-drill cores (pl. 1) which had been taken to explore the rich oil-shale deposits of the formation. The rich oil shale is mainly in the upper 400-500 feet of the Parachute Creek Member; hence most of the core examined is mainly from the upper 400-500 feet of the Parachute Creek Member.

Four of these seven cores were studied in great detail, and some of the beds of another were examined closely. Two of the cores were examined only cursorily. In addition, some samples collected from surface exposures as well as some samples from cores beyond the limits of the area were studied in some detail. The studies included the examination of more than 300 thin sections and approximately the same number of X-ray diffractometer patterns.

Acknowledgments

Appreciation is expressed to numerous individuals, two oil companies, and the U.S. Bureau of Mines. Of men in the Geological Survey, Thomas A. Hendricks acted in a general advisory capacity during the study, and John R. Donnell, who had worked in the area for many years, was helpful in too many instances to enumerate. William B. Cashion, who has worked on the Green River Formation in both Colorado and Utah, also has been very helpful. Ray E. Wilcox has advised on the petrography, and Leonard G. Schultz and Theodore Botinelly have advised on the interpretation of many X-ray analyses.

Thomas Walker, formerly a consultant in exploratory drilling for oil shale in the formation, allowed the sampling of two cores. The Shell and Equity Oil Companies also allowed the sampling of cores. The U.S. Bureau of Mines, through Kenneth E. Stanfield, furnished samples from a core and allowed access to their laboratory facilities at Laramie, Wyo.

SUMMARY OF THE STRATIGRAPHY OF THE GREEN RIVER FORMATION

The Green River Formation is a lake deposit of Eocene age, and in the area of this study its total thickness ranges from about 2,000 to 5,000 feet (J. R. Donnell and D. C. Duncan, oral commun., 1964). The original thickness in the basin is unknown, as the uppermost portion has been eroded away, but the thick deposit consists of sandstone, siltstone, papery shale, marlstone (including oil shale), and some highly altered ash-fall tuff beds and water-washed tuffaceous rocks. Figure 2 is a diagrammatic sketch from west to east across the area and shows the five members which have been recognized and their stratigraphic relations.

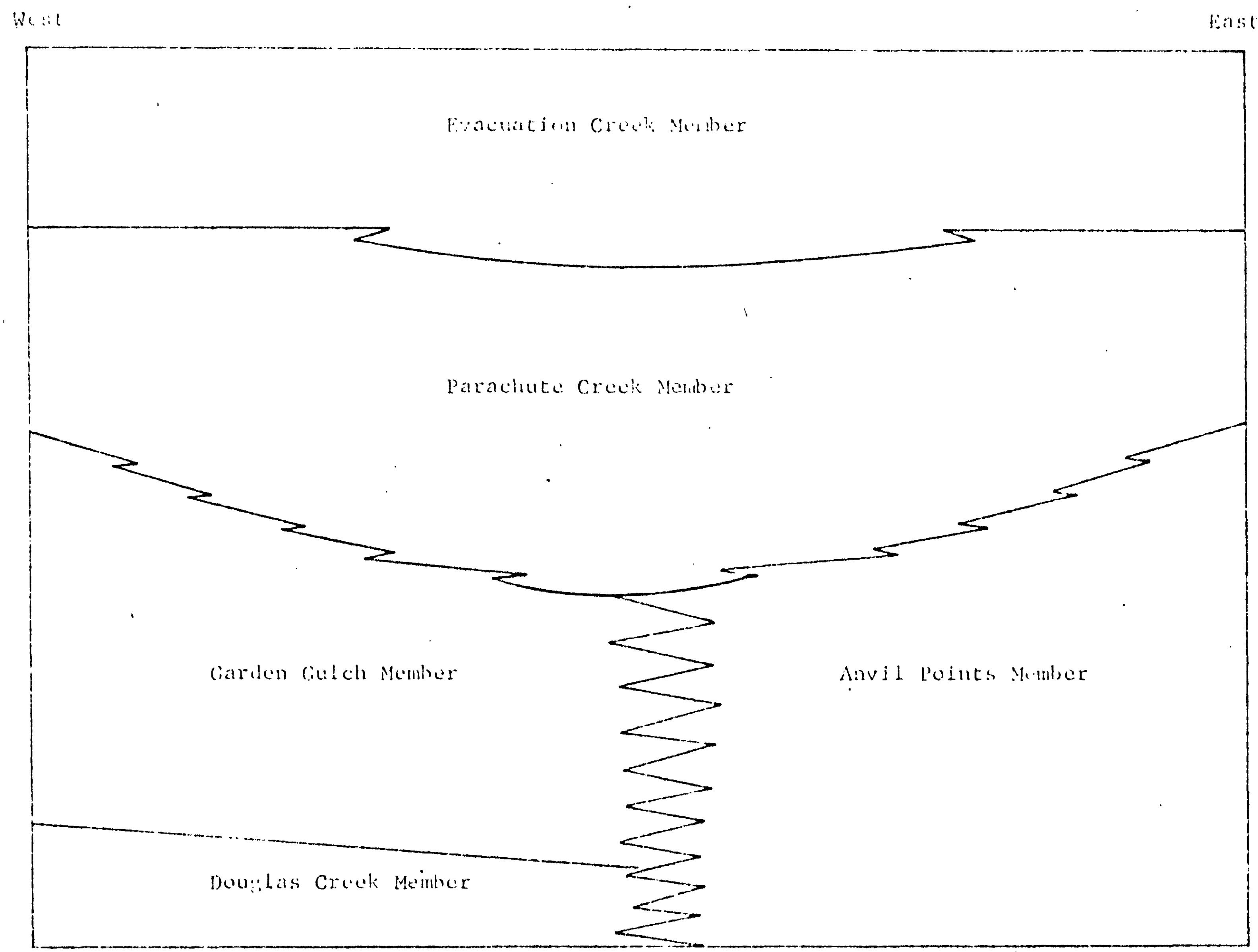

Figure 2.--Diagrammatic sketch from west to east across the area showing the members of the Green River Formation.

The formation is somewhat heterogeneous. This heterogeneity is greatest in the lower part of the formation--in the Douglas Creek, Garden Gulch, and Anvil Points Members (Donnell, 1961, p. 848-852). These three members are composed mainly of sandstone, shale, and marlstone, and they interfinger toward the center of the basin. The Parachute Creek Member is relatively uniform, consisting mainly of oil-yielding dolomitic marlstone, though it contains the altered ash falls and water-washed tuff which are the subject of this report. The Evacuation Creek Member, the uppermost subdivision of the formation, is composed mainly of sandstone, siltstone, water-washed tuffaceous rocks, and, in the lower half, fairly numerous thin units of marlstone and some oil shale.

THE ALTERED TUFFACEOUS ROCKS OF THE GREEN RIVER FORMATION

This paper is essentially confined to a description of the numerous altered ash-fall tuff beds and water-washed tuffaceous rocks of the upper part of the Parachute Creek Member, where these beds are abundant and usable as markers. It should be mentioned at the outset, however, that the complete story of the actual quantitative importance of tuffaceous debris throughout the Green River Formation is as yet unknown. Much of the marlstone and oil shale contains some tuffaceous debris, as was noted first by Bradley (1928, p. 73). This observation also has been confirmed recently by R. L. Smith (oral commun., 1962), who has observed important amounts of tuffaceous material in the marlstone and oil shale of the formation.

The Shell Oil Co. Greeno 1 core, the deepest core taken in the basin, contained only a few tuff beds about 1/8 inch thick in the lower part of the Parachute Creek Member, and the Garden Gulch Member apparently contains none. However, specimens taken from this core show that the lower part of the Parachute Creek and at least part of the Garden Gulch Member contain many very thin beds of dolomitic marlstone ranging in thickness from about 1/4 inch to 6 inches which contain abundant feldspathized tuffaceous debris. The lower 400-600 feet of the Evacuation Creek Member has been examined hurriedly, but this portion of the member appears to be composed predominantly of water-washed tuff with some thin units of marlstone and oil shale, some of which may be tuffaceous. The upper part of the Evacuation Creek Member appears to contain thin beds of altered tuff as well as carbonate-bearing water-washed tuff which is dominantly sandstone.

THE ALTERED ASH-FALL BEDS OF THE PARACHUTE CREEK MEMBER

General characteristics

If one counts beds as thin as 1/8-1/4 inch thick, there are over 50 ash-fall tuff beds in the upper 500-600 feet of the Parachute Creek Member of the Green River Formation in the Piceance Creek Basin. Essentially all these beds are in and just below the so-called upper oil-shale zone of the formation. This zone has been widely studied because of its rich and readily accessible oil reserves, and some "units within the * * * zone have been given separate designations because of their special importance" to the stratigraphy (Donnell, 1961, p. 855). Therefore, this zone will be described at this point along with some of the units of the zone in order to refer to certain tuff beds shown on plates 2 and 3.

This upper oil-bearing unit is about 300 to about 620 feet thick (Donnell, 1961, p. 854), and it extends upward from the upper barren zone of Duncan and Denson (1949) and the barren zone of Donnell (1961, p. 854) to the base of the Evacuation Creek Member. This barren zone of these workers has been referred to informally by them as B groove, and this designation is used in this report. The oil-rich Mahogany bed, about 3 to 10 feet thick, is about 50 to 150 feet above B groove and is the best marker bed in the upper oil-shale zone. A groove is another interval of barren marlstone about 100 to 200 feet above B groove. These three units are more important as stratigraphic markers in the area than are the altered tuffs; hence, they are shown on plates 2 and 3, and it is convenient to relate the position of the tuff beds to the three units.

The altered ash-fall tuff beds are most abundant in the lower part of the upper oil-shale zone and a short stratigraphic distance below this zone. The lowest altered tuff that has been found at surface exposures is about 300 feet below the Mahogany bed, is about 1 inch thick, and was found in sec. 16, T. 6 S., R. 97 W. Two thin beds about the same stratigraphic distance below the Mahogany bed and about 1 and 2 inches thick, respectively, are present in the Weber Oil Co. Juhan 1 core in the northeastern part of the basin. The main interval of altered ash falls in the area is believed to start about 200 to 250 feet below the Mahogany bed and to extend upward to about 150 to 200 feet above it (pls. 2 and 3).

None of the altered tuff beds are thick units. They range in thickness from about 1/8 inch to about 5 feet, and most of them are between 1/8 inch and about 6 inches thick. They range in color from white to gray, though some are stained tan to light brown by hydrocarbons. Nearly all beds show a silty to sandy texture to the unaided eye.

Key beds and groups of beds

The more than 50 beds mentioned above cannot all be shown on plates 2 and 3, nor can all of these beds be discussed. Only the most conspicuous beds and groups of beds will be discussed in this brief report.

Beds below B groove

Thin beds of altered tuff become abundant, at least in some areas, at a stratigraphic level starting about 150 feet below B groove (pls. 2, 3). This is most apparent in the northeastern part of the area in the Weber Oil Co. Juhan 1 core, where nine beds, about 1/2 inch to 6 inches thick, were noted (pl. 2). Surface exposures do not permit a detailed study of this interval, and only a few cores have been taken. However, the U.S. Bureau of Mines A core, the Savage Oil Shale Development Co. Camp 1 core, and the Gabbs Exploration Co. Mullins 2 core all indicate several episodes of volcanism during this interval of sedimentation (pls. 2, 3). The reason for the complete absence of similar beds in the Shell Oil Co. Greeno 1 core is unknown; the most logical explanation is that the beds are present but were not recovered by the core barrel in this hole.

The alteration of the tuff beds in this interval is analcitization and feldspathization. In some beds the alteration of the original fine glass has produced chiefly albite, in other beds the chief alteration product is analcite, and in some beds there is an appreciable amount of both of these minerals. In all cases the crystals which have developed from the original glass are less than 0.25 mm across. For a detailed description of these rocks the reader is referred to the section on petrography.

The direction of the source for this group of tuffs is believed to have been to the north[redacted] of the area, as indicated by the increase in thickness as well as in the number of beds in this direction. Only beds about 1/2 inch thick or more have been plotted on plates 2 and 3, and on this basis the greatest number, along with one bed 6 inches thick in the Juhan 1 core in the extreme northeastern part of the area, indicate that the source was to the northeast.

Beds between A and B grooves

Many beds of minor thickness are present in places between A and B grooves, but only those beds of most importance are considered here. The four most important beds are shown on plates 2 and 3; these are the curly bed, the F bed, the Mahogany marker, and the false marker.

The curly bed occurs between about 5 and 10 feet above B groove. This bed is a few inches to about 1.5 feet thick in the area, and it characteristically changes in thickness within short lateral distances, even pinching and swelling conspicuously at individual exposures. In spite of these characteristic changes in thickness, there seems to be a general thickening of the bed to the west, possibly indicating a westerly source for the original ash fall. In Hells Hole Canyon, in sec. 22, T. 10 S., R. 25 E., in Utah, 3 miles west of the Colorado State line, the bed reaches a thickness of 3 feet at one point. Some specimens contain dark-colored stringers of collapsed pumice as thin contorted streaks as much as 1/2 inch long. These streaks have led to the bed's being referred to as the lower wavy bed by some workers. Specimens collected from surface exposures and from some of the cores contain fairly conspicuous trapezohedrons of analcite as much as 0.25 mm across and readily visible with a hand lens, but the Wasatch Development Co. Elizabeth 1 core indicates that near the center of the basin the alteration of the original glass changes from the typical analcitization to feldspathization. This is the general rule for virtually all the altered tuff beds.

The F bed is about 6 to 12 feet above the curly bed. It ranges in thickness from about 2 inches to about 1 foot, but, according to Donnell (1961, p. 856), the thickness of about 2 inches is typical in the area. Where analcitized, the trapezohedrons of this mineral are smaller and much less conspicuous under a hand lens than those in the closely associated curly bed, but commonly the F bed contains short, contorted streaks of collapsed pumice similar to those in the curly bed.

The Mahogany marker is the best known of all the altered tuff beds of the Green River Formation. It was known to early workers (Bradley, 1929, p. 2) as the "marker bed." It was so named during early studies of oil shale of the formation in Utah and Colorado because of its close association with the rich oil-bearing Mahogany bed. The "marker" is about 5 to 15 feet above the Mahogany bed, and ranges in thickness from about 3 inches in the northern part of the area to about 6 inches in the southern part. This gradual southward thickening may indicate a southerly source for the bed. Typically, this altered ash fall contains over 50 percent analcite, many of the anhedral to nearly perfect trapezohedrons ranging from about 0.2 to 0.4 mm across and visible to the naked eye.

The false marker is generally about 1 inch thick and commonly occurs about 10 feet above the Mahogany marker, but the interval of oil shale between the two altered tuff beds seems to thicken markedly from near the center of the basin northeastward, and the false marker has been tentatively placed at a position nearly 40 feet above the Mahogany marker in the Juhan 1 core. Except in the cores from the Wasatch Development Co. Elizabeth 1 and the Shell Oil Co. 1 holes, the false marker is characterized by abundant trapezohedrons of analcite which are as much as 0.4 mm across.

There are commonly two thin beds of altered tuff within a few feet of the Mahogany bed, and one is within the Mahogany bed in places. These three beds are thin and erratic in their occurrence in cores in the area, presumably not having been recovered in all cases; hence, they are not shown on plates 2 and 3, but they deserve mention. One of the two closely associated beds is about 1 to 2 feet above and the other 1 to 2 feet below the rich oil-bearing bed. Each is about 1/2 inch thick except in the Bureau of Mines A core, where the overlying tuff is more than 1 inch thick. The altered tuff within the central part of the Mahogany bed has been seen in only one or two cores, where it is about

1/4 inch thick, but, according to W. B. Cashion (oral commun., 1964), this bed thickens to the west in westernmost Colorado and eastern Utah, where it definitely becomes continuous.

The wavy bed

The wavy bed is about 20 to 80 feet above A groove and is probably the most distinctive bed in the Green River Formation. Its distinctive character, for which it is named, is caused by the general presence of abundant, flattened, wavy clots of collapsed pumice similar to the collapsed pumice of some welded tuffs (fig. 8). This collapsed pumice is most abundant in the bed at the east side of the basin, where on plane surfaces the collapsed fragments stand out as dark-colored wavy stringers as much as 1-1/2 inches long. These distinctive stringers become smaller and less abundant to the west. None were noted in Hells Hole Canyon, in sec. 22, T. 10 S., R. 25 E., in Uintah County, Utah, about 3 miles from the Colorado-Utah State line.

The wavy bed is not in reality a single bed but is the product of several successive ash falls and consequently a multiple ash-fall unit. Near the eastern part of the area the bed at the base of the unit is about 6 inches to 1 foot thick, the overlying beds tending to become progressively thinner upward. Near the top of the unit in this part of the area some beds or individual ash falls are about 1 inch thick. Individual ash falls near the top of the unit in eastern Utah are less than 1/4 inch thick. At one locality visited by the writer and in one of the cores examined, laminae or thin beds of carbonate separate some of the original ash falls. The fact that this unit is composed of several ash falls that can be recognized as individual beds may make it possible to use the unit as a stratigraphic marker in the Wyoming portion of the formation.

The wavy bed as a unit is the thickest of the ash-fall intervals in the Parachute Creek Member, and is believed to be the thickest ash-fall unit in the Green River Formation in the area. It reaches a maximum known thickness of 5 feet at an exposure near the center of sec. 6, T. 4 S., R. 94 W., where it is well exposed in a roadcut on upper Piceance Creek. It thins to the west and is 1.8 feet thick in the Gabbs Mullins 2 core, and J. R. Donnell (oral commun., 1964) reports a minimum thickness of about 1 foot at some exposures along the west side of the Piceance Creek Basin. However, farther west it is 2 feet thick in sec. 16, T. 11 S., R. 25 E., in eastern Uintah County, Utah; this locality is about 4 miles west of the Colorado State line. *In the Green River Basin, Wyoming, it is [illegible] 1-foot thick. It [illegible] be identified [illegible] multiple [illegible]* Analcite is the chief alteration product of the original glass of the unit over nearly all the area, but crystals of the mineral, though ranging from about 0.05 to 0.3 mm across, are commonly anhedral to subeuhedral, and some portions of the unit do not have the distinctly sandy appearance to the unaided eye that is common in the case of most beds between A and B grooves; instead, many portions of the unit break and weather to a relatively smooth surface.

The definite westerly and northerly thinning of this ash-fall unit probably indicates a~~n easterly or~~ southeasterly eruptive source.

The upper zone of altered tuffs

The upper zone of altered tuffs is in a 50- to 75-foot interval of oil shale just above the wavy bed. The base of this interval appears to be about 10 to 15 feet above the wavy bed at most places in the basin (pls. 2, 3). The exact number of beds, including those less than 1/2 inch thick, and their precise stratigraphic distribution are unknown. However, there appear to be at least nine main beds more than 1/2 inch thick in the southeastern part of the area and essentially as many in the south-central and southwestern parts. This number decreases northward, in spite of the probability that some beds did not enter the core barrel in the Shell Oil Co. Greeno 1 core, and there are definitely fewer beds in the Weber Oil Co. Juhan 1 core in the northeastern part of the area. Presumably, the source of these beds was to the south.

The thickness of the main beds--those plotted on plates 2 and 3--ranges from about 1/2 inch to about 6 inches. As in the wavy bed, they all lack the conspicuous granular or sandy texture to the unaided eye that is shown by the altered tuffs between A and B grooves. The analcite crystals, though some are nearly as large as those in the beds between A and B grooves, do not stand out as conspicuously on either a weathered or freshly broken surface. Tiny biotite plates in some of the beds are visible to the unaided eye, however.

The white bed

More than 10 thin beds of altered ash falls have been noted in places between the upper zone of altered tuffs in the Parachute Creek Member and the overlying Evacuation Creek Member of the Green River Formation. These thin beds, nearly all of which are less than 1/2 inch thick, are most abundant in the southern part, south of the location of the Wasatch Development Co. Elizabeth 1 core, and none were noted at exposures along lower Piceance Creek at the northern margin. Within this stratigraphic interval, however, a distinctive bed of white altered tuff has been noted in three cores; it is about 1 inch thick, and is shown on plates 2 and 3. It is present 20-30 feet below the Evacuation Creek Member in the Gabbs Mullins 2, the Savage Camp 1, and the Shell Greeno 1 cores. This bed is very distinctive because of its white color and because it appears to be the last ash fall in the Parachute Creek Member.

PETROGRAPHY

The two types of altered ash-fall beds

There are two basic types of altered ash-fall beds in the Parachute Creek Member of the Green River Formation. The analcitized type is fairly well known, having been described in considerable detail from several stratigraphic levels and localities in both Utah and Colorado by Bradley (1928; 1929, p. 1-6), and some analcitized beds have been used as stratigraphic markers by later workers in these States (see "Historical summary"). The other type of alteration was noted during the course of this investigation. In this second type analcite is absent, and the original volcanic glass of the beds has been altered to very fine grained feldspar, quartz, and opal--a type of alteration formed mainly in the central part of the basin (pls. 2, 3).

There is no means of determining the original composition of the ash falls, but the phenocrysts and the apparent absence, or very small amount, of potash feldspar in the matrix of most of the altered rocks indicate that the original glassy ash of most of the beds must have been dacitic.

The analcitized type

The analcite, which forms about 40 to 65 percent of the analcitized tuffs, occurs almost entirely as trapezohedrons in varying stages of perfection. In many specimens there is a gradation from ill-formed to relatively well formed crystals; in some, most of the crystals are well formed. In a few specimens most of the trapezohedrons are poorly formed, and at an extreme stage some of the analcite is subrounded or irregular in shape. The crystals range from about 0.03 to about 0.4 mm across.

The analcite crystals invariably show some reticulate cracking and contain varying amounts of tiny inclusions, though some have a clear uncracked rim which extends for a few microns inside the crystal boundary. Clear second-generation analcite fills tiny cracks in some crystals, as previously noted by Bradley (1929, p. 3). In most specimens tiny inclusions are abundant, giving the analcite a distinctly clouded appearance (figs. 5, 6), but in some specimens the crystals are fairly free of included foreign minerals. The inclusions consist chiefly of pyrite, with lesser amounts of opal and calcite, tiny rhombs of dolomite, and rare prisms of feldspar. These included grains or crystals range in size from about 2 to 10 microns across or in greatest dimension. Their presence leads one to believe that the analcite formed so rapidly that the included minerals were not pushed into the interstices between the growing crystals but instead were entrapped inside them.

The interstices between the dominant analcite crystals are filled almost completely by a fine-grained aggregate of feldspar, opal, quartz, carbonate, and pyrite. The feldspar is mainly a very pure albite close to $Ab_{95}An_5$, as shown by X-ray analyses. Tiny prisms of this mineral are about 10 to 40 microns long and compose as much as 20 percent of some specimens. Potash feldspar as prisms of about this size generally occurs in very small amounts; X-ray examination indicates that 5 percent or less is present in most of these rocks. The opal and quartz are interstitial to the tiny feldspar prisms. Anhedral grains of these silica minerals range from less than 0.2 micron to about 3 microns across in some specimens. In other specimens nearly all the grains are microcrystalline quartz, ranging from about 2 to 5 microns across and having a distinctly cherty appearance. Intermixed carbonate comprises from less than 5 to more than 15 percent, though 5 to 10 percent is most common, and both calcite and dolomite are present in varying proportions. The calcite is in anhedral grains about 2 to 10 microns across. The dolomite occurs as rhombs about 5 to 20 microns across that commonly are within small patches of calcite grains. Pyrite composes but a small part of the fine-grained aggregate, ranging in amount from less than 1 percent to about 2 percent. It is present as dust-size particles, as tiny anhedral grains which commonly are in aggregates, and as cubes as much as 25 microns across. In a few specimens tiny grains form a rim around the analcite crystal. Pyrite also has been identified in feathery blades as much as 0.5 mm in length. In this form it probably is pseudomorphic after marcasite.

The accessory minerals are apatite and zircon, some of which are within and some of which are interstitial to the analcite crystals. Apatite has been noted in most of the slides examined. Generally, the tiny prisms are 10 to 20 microns long, but larger prisms as much as 50 microns long are not uncommon, and one tuff bed about 35 feet below the Mahogany bed in sec. 6, T. 4 S., R. 94 W., carried crystals as much as 0.25 mm long. The terminal faces of the crystals are not well developed. In most cases the prisms have subrounded ends, and where terminal faces are developed they are generally of poor quality. The zircon prisms are relatively rare, are about 20 to 50 microns long, and have poorly to well developed terminal faces. Some are singly and some are doubly terminated. In some specimens the crystals are subrounded and 20 to 30 microns across.

Tiny phenocrysts comprise from less than 5 to more than 20 percent of the specimens from the analcitized tuff beds. Plagioclase is ubiquitous and the most abundant of the phenocrysts. Quartz occurs in all but a few slides examined, but it is not present in appreciable amounts. Biotite is present in trace or small amounts in many specimens, though it exceeded plagioclase in amount in two slides examined. Hornblende is scarce, and pyroxene and sanidine(?) are rare.

The plagioclase phenocrysts comprise from less than 5 to 20 percent of the specimens examined, occurring as crystals and crystal fragments scattered at random through the altered matrix. These crystals and crystal fragments range from about 0.06 to 0.4 mm in greatest dimension and show the very thin twin lamellae that are characteristic of the plagioclase of volcanic rocks. Many of the lamellae are as narrow as 1 micron. In extreme cases the lamellae are less than 1 micron wide at one edge of a crystal or crystal fragment, and as they extend toward the opposite edge they pass below the resolving power of the microscope and disappear from view. These phenocrysts are sodic andesine (approximately An_{35}) where not albitized, but most show slight to moderate albitization. The albitization is most pronounced along cleavage planes and fractures, becoming less pronounced toward the interior of the crystals, and some of the phenocrysts have a thin overgrowth of clear albite.

The quartz phenocrysts are angular to splintery crystal fragments about 0.05 to 0.2 mm across, scattered at random through the altered matrix. Never an important constituent, they generally comprise about 1 to 3 percent of the rocks. The biotite phenocrysts are tiny unaltered hexagonal plates, some of which have ragged edges, ranging from about 0.025 to 0.75 mm across. All of the plates seem to be very similar optically, as all are highly pleochroic, with α pale olive tan and β and γ clove brown. These plates are randomly oriented and are present in varying amounts in the specimens examined. They are absent from some specimens, present in small amounts in others, and compose about 5 percent of a few specimens, mainly from the southeastern and northeastern parts of the area. In two rare specimens they compose about 15 percent of the rock. Hornblende phenocrysts as crystals and crystal fragments about 0.025 to 0.25 mm long are noteworthy only in some beds in the U.S. Bureau of Mines A core; here they compose as much as 5 percent of a few specimens. Crystal fragments of augite were noted in one specimen collected in sec. 6, T. 4 S., R. 94 W., and in another specimen collected in sec. 16, T. 11 S., R. 25 E., in eastern Utah, about 4 miles west of the Colorado State line. These fragments composed less than 5 percent of the two specimens, and ranged in greatest length from about 0.1 to 0.25 mm. A trace of sanidine(?) as tiny crystals less than 0.1 mm in greatest dimension was noted in one slide.

The following table gives a chemical analysis and calculated mineral composition of an extreme type of analcitized tuff.

Chemical analysis and calculated mineral composition of an extreme type of analcitized tuff (after Bradley, 1929, p. 6)

Chemical analysis			Calculated mineral composition: By weight	Calculated mineral composition: By volume
SiO_2--------	52.54	Analcite-----------------	65.84	70.34
Al_2O_3-------	15.78	Chalcedony, quartz, and opal-------------------	15.66	14.49
Fe_2O_3, FeO -----	4.54	Sanidine and orthoclase--	3.71	5.67
MgO----------	.63	Limonite(?)--------------	11.37	7.58
CaO---------	.36	Pyrite-------------------	2.73	1.31
Na_2O--------	8.63	Calcite------------------	.69	.61
K_2O---------	1.16			
H_2O^---------	.05			
H_2O^+--------	8.96			
CO_2---------	.29			
FeS_2--------	2.74			
Bituminous material--	3.93			
	99.61			

The feldspathized type

The feldspathized type of altered tuff is most common in the center of the basin, as indicated by plate 2. In the Shell Oil Co. Greeno 1 core at the center of the basin essentially all the beds are characterized by a matrix whose dominant constituent is microcrystalline feldspar. A lesser number of beds in the Wasatch Development Co. Elizabeth 1 core about 7 miles southward show this type of alteration, and still farther southward only two beds in the Savage Oil Shale Development Co. Camp 1 core are feldspathized. At the northeast end of the basin, in the Weber Oil Co. Juhan 1 core, four beds are feldspathized. The Gabbs Exploration Co. Mullins 2 core, the Tell Ertl Theo 1 core, and the U.S. Bureau of Mines A core, which are, respectively, near the western, eastern, and southeastern margins of the basin, do not contain any feldspathized ash falls. Hence, it is apparent that the feldspathization of the tuff beds decreases away from the center of the basin.

The matrix of these rocks is extremely fine grained, as shown on figures 3 and 4. These plates also show for some specimens the peculiar reticulate appearance of the matrix, which is caused by numerous microlites of feldspar and possibly by a few flattened relict shards as well as a trace of relict Y-shaped shards. The matrix is mainly feldspar, quartz, and opal, with varying amounts of calcite and dolomite. The feldspar of the matrix composes about 40 to 80 percent of the rocks and is a nearly pure albite, as shown by X-ray analyses. A chemical analysis and normative minerals of an extreme type of albitized tuff are given on page 19. Potash feldspar is relatively rare, but it is present in appreciable amounts in some specimens, as indicated by X-ray diffractograms; and in one unusual specimen collected from B groove at a depth of 308 feet in the Weber Oil Co. Juhan 1 core (see analysis, p. 20) most of the feldspar is a pure orthoclase or adularia, as shown by its indices of refraction. The feldspar microlites are about 5 to 50 microns long; some of the smallest are about 0.2 micron wide. Quartz and opal are interstitial to the feldspar microlites, and individual grains of these silica minerals range from below the resolving power of the microscope to about 3 microns across. These minerals generally compose about 15 to 30 percent of the specimens. Interstitial calcite and dolomite are variable in amount; some specimens contain less than 5 percent, but some contain as much as 20 percent. The calcite occurs in grains about 1 to 25 microns across. The dolomite occurs as rhombs about 5 to 50 microns across. Pyrite is relatively unimportant in the interstitial aggregate, composing from less than 1 to about 2 percent of these rocks; it occurs as grains, aggregates of grains, and cubes. The grains range from about 1 micron to as much as 0.25 mm across, and aggregates of grains are nearly 1 mm across in some specimens; the cubes are 5 to 50 microns across.

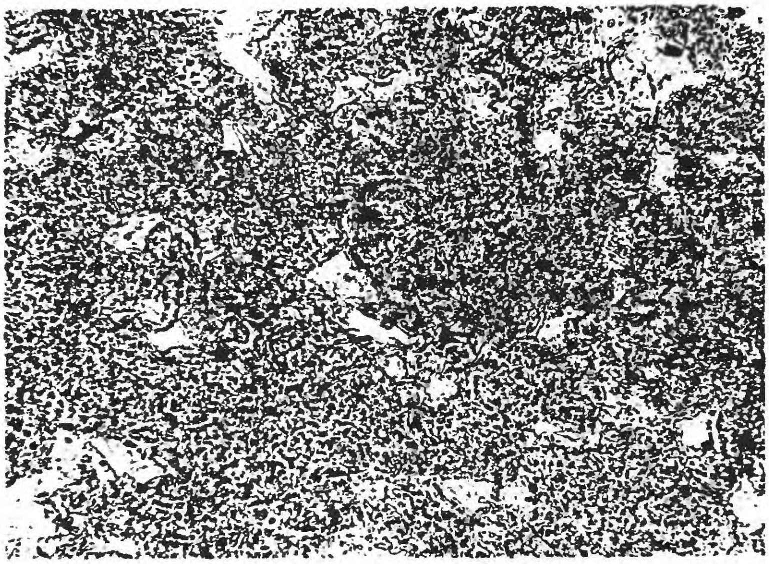

Figure 3.--Photomicrograph of a thin section of an albitized tuff bed from a depth of 475 feet in the Weber Oil Co. Juhan 1 core. The pronounced reticulate appearance of the matrix is due to feldspar microlites, flattened relict shards, and some relict Y-shaped shards. The black grains are pyrite. Crossed nicols. X 150.

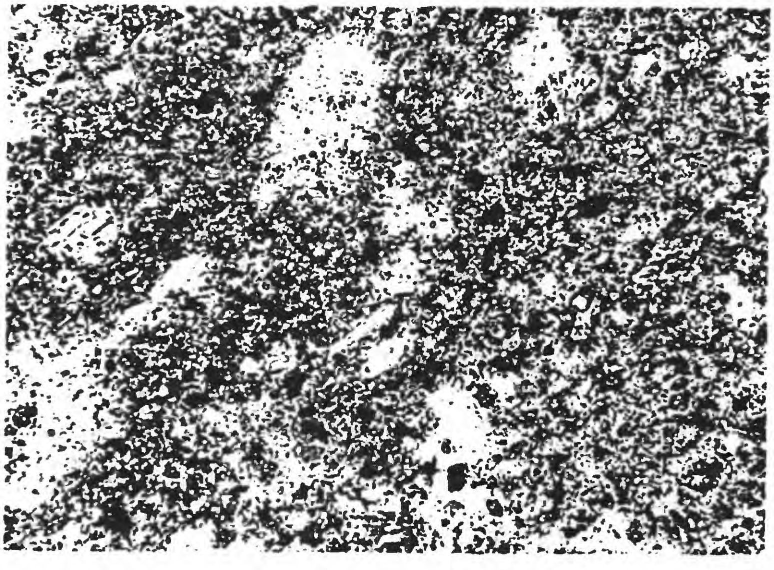

Figure 4.--Photomicrograph of a thin section on an albitized tuff bed from a depth of 400 feet in the Weber Oil Co. Juhan 1 core. The plagioclase phenocrysts are highly albitized with overgrowths that grade outward into the matrix of albite microlites, opal, and microcrystalline quartz. The black grains are pyrite. Crossed nicols. X 150.

Chemical analysis and normative minerals of an extreme type of albitized tuff

[From 1-inch bed at a depth of 402 feet in the Weber Oil Co. Juhan 1 core. Analysis by U.S. Geological Survey. Organic matter determined by Irving Frost]

Chemical analysis		Normative minerals	
SiO_2	62.86	Albite	86.98
Al_2O_3	17.35	Potash feldspar	Trace
MgO	.01	Quartz	3.12
CaO	.12	Pyrite	2.06
Na_2O	10.27	Calcite	Trace
K_2O	.18	Dolomite	Trace
TiO_2	.01	Apatite	Trace
P_2O_5	.01	Organic matter	7.14
MnO	.00		
F	.01		
Cl	.00		
FeS_2	2.06		
CO_2	.06		
H_2O^-	.09		
Organic matter	7.14		
	100.17		

Chemical analysis and normative minerals of a feldspathized tuff in which orthoclase is the dominant constituent

[From a 5-inch bed at a depth of 308 feet in the Weber Oil Co. Juhan 1 core. Analysis by U.S. Geological Survey. Organic matter determined by Irving Frost]

Chemical analysis		Normative minerals	
SiO_2	62.81	Orthoclase	52.26
Al_2O_3	16.93	Albite	16.24
MgO	.12	Quartz	17.82
CaO	.20	Pyrite	2.17
Na_2O	1.90	Apatite	Trace
K_2O	8.81	Dolomite	.46
TiO_2	.04	Calcite	.13
P_2O_5	.02	Organic matter	4.58
MnO	.01		
CO_2	.16		
F	.02		
Cl	.00		
FeS_2	2.17		
H_2O^-	.21		
Organic matter	4.58		
	97.98		

The accessory minerals are apatite and zircon, as in the analcitized rocks. Apatite is by far the most abundant. It occurs in all or essentially all specimens examined as tiny prisms, mainly with subrounded ends and commonly 10-30 mm long, but doubly terminated prisms as much as 0.5 mm long have been noted. Zircon is rare; where present, it occurs as tiny poorly terminated prisms and subrounded grains.

The phenocrysts of the feldspathized rocks are, for all practical purposes, limited to plagioclase and quartz. The plagioclase phenocrysts are crystals and crystal fragments ranging in greatest dimension from about 0.05 to 0.3 mm, and compose from less than 5 to about 20 percent of the individual specimens; all the phenocrysts are moderately to highly albitized. In the Shell Oil Co. Greeno 1 core the plagioclase crystals and fragments also are flecked with grains of calcite that are about 1 to 10 microns across. Overgrowths of albite are common on these phenocrysts, and in many cases the outer boundary of the overgrowth is irregular to fuzzy; in places the overgrowths almost grade into the albite of the matrix (fig. 4). The quartz phenocrysts are angular crystal fragments about 0.05 to 0.1 mm across; they are absent or nearly so from a few specimens, and seldom comprise more than 5 percent in any specimen examined. Sanidine(?) phenocrysts are extremely rare; where tentatively identified in one specimen they are about 0.1 mm in greatest dimension and are very clear and unaltered. A few plates of original biotite about 0.1 to 0.2 mm across exist in a few specimens as bleached ghosts.

Key beds and groups of beds

Beds below B groove.--This sequence of altered tuff beds is the least definite of all the beds as a marker sequence. Few cores have penetrated the section below B groove, and one of these failed to show altered tuff beds in this part of the section (see p. 9, and pls. 2 and 3). However, this sequence probably will become significant in the future, as it represents the lowest sequence of distinct ash-fall beds in the Piceance Creek Basin.

Both types of alteration, analcitization and feldspathization, are represented, as shown by plates 2 and 3. This is most apparent in the Weber Oil Co. Juhan 1 core in the northeastern part of the basin and least apparent in the U.S. Bureau of Mines A core in the southeastern part and in the Gabbs Exploration Co. Mullins 2 core in the western part. In the last two named cores only analcitized beds were noted. Judging from the increase in feldspathization toward the center of the basin in beds above B groove, it is probable that future cores drilled in this part of the basin will show all beds feldspathized in this interval below B groove.

Tiny phenocrysts as crystals and crystal fragments are present in all the specimens examined from this interval. Plagioclase phenocrysts are in all the specimens, quartz is in essentially all, and plates of biotite are not uncommon in the analcitized specimens. Most of the plagioclase phenocrysts are about 0.05 to 0.025 mm across and comprise about 2 to 10 percent of the specimens; they are highly albitized in the feldspathized rocks and slightly to moderately albitized in the analcitized rocks. Fragments of quartz are about 0.025 to 0.1 mm across. Plates of biotite about 0.025 to 0.2 mm across are not uncommon in trace or small amounts in some analcitized specimens from the U.S. Bureau of Mines A core and the Weber Oil Co. Juhan 1 core. One bed at a depth of 462 feet in the Juhan core contains about 15 percent biotite. Plates of this mineral are absent or present only as relicts in the feldspathized specimens.

The matrix of the analcitized beds consists of about 50 to 65 percent anhedral to subeuhedral crystals of analcite, the interstices between these crystals being filled mainly by opal, quartz, and feldspar. The analcite crystals are mainly about 0.02 to 0.1 mm across and in general are both smaller and less well formed than those in the altered tuff beds above B groove. They also, in general, seem to contain fewer inclusions, and a slight to moderate cloudiness seems more commonly the result of reticulate cracking. The feldspar microlites in the interstices form about 15 to 20 percent of the specimens. For the most part, these microlites are nearly pure albite, ranging in length from about 10 to 40 microns. Microlites of potash feldspar comprise more than 5 percent of the rock in two specimens collected from near the top of the interval. One specimen is from the U.S. Bureau of Mines A core and the other is from the Weber Oil Co. Juhan 1 core; both probably are from the same altered ash fall. The opal and quartz grains between the feldspar microlites are less than 1 to about 3 microns across and compose about 5 to 20 percent of the specimens. Also present as interstitial matter are carbonate and pyrite. The carbonate consists of both calcite and dolomite in most specimens and occurs as grains and rhombs about 1 to 50 microns across; these minerals comprise 1 to 10 percent of the specimens examined. Pyrite as grains and cubes 1 to 50 microns across compose 1 to about 5 percent of the specimens.

Microlites of feldspar form 55 to 80 percent of the feldspathized beds, are about 5 to 40 microns long, and are essentially all albite except in two specimens where albite and orthoclase microlites are present in approximately equal amounts. One of these two specimens is from a depth of 737 feet in the Savage Oil Shale Development Co. Camp 1 core, the other from a depth of 851 feet in the Wasatch Development Co. Elizabeth 1 core; both specimens apparently are from the same ash fall. Opal and microcrystalline quartz compose about 10 to 35 percent of the beds, and the anhedral grains are less than 1 to about 5 microns across. Calcite, dolomite, and pyrite occur in about the same amount and in comparable habit and grain size as in the analcitized beds.

One specimen collected from a depth of 542 feet in the Weber Oil Co. Juhan 1 core is intermediate between the feldspathized and analcitized tuffs, and contains about 30 percent analcite and about 45 percent feldspar.

Beds between A and B grooves.--The significant beds in this stratigraphic interval are the curly bed, the F bed, the Mahogany marker, and the false marker. All are analcitized in the cores examined from around the edge of the basin; that is, in the Juhan 1, the Gabbs Mullins 2, the Savage Camp 1, and the U.S. Bureau of Mines A cores. This alteration also was noted at exposures in sec. 6, T. 4 S., R. 94 W., at the east edge of the area and in sec. 11, T. 1 N., R. 97 W., at the north edge. All four beds are feldspathized in the Elizabeth 1 core from near the center of the basin, and though the curly and F beds were not recovered from the Shell Greeno 1 core at the approximate center of the basin the Mahogany marker and false marker are feldspathized in this core.

The closely associated curly and F beds are similar petrographically, and both are believed to have been quartz latite tuff originally. The beds contain about 2 to 10 percent phenocrysts of plagioclase and quartz, and, where analcitized, at least a trace of biotite or relict biotite. In the U.S. Bureau of Mines A core, the curly bed contains a maximum of about 5 percent biotite. The altered base of the analcitized specimens generally is composed of about 50 to 60 percent poorly to fairly well formed trapezohedrons of analcite which range from nearly clear to highly clouded by inclusions (fig. 5). These crystals are highly variable in size; though reaching a maximum size of about 0.4 mm in diameter in the curly bed, they are generally smaller. Most of these crystals in the curly bed are about 0.1 to 0.2 mm in diameter; in the F bed some are as small as 0.01 mm in diameter, though 0.05 to 0.15 mm size is more common. The minerals interstitial to the analcite are microlites of albite, potash feldspar, opal, and microcrystalline quartz, varying amounts of carbonate, and a trace of pyrite. Neither bed was recovered in the Shell Oil Co. Greeno 1 core from the approximate center of the basin, but in the Wasatch Development Co. Elizabeth 1 core from near the center of the basin both beds are feldspathized. Here the two beds contain about 5 percent phenocrysts of plagioclase and quartz and the F bed contains a trace of altered biotite. The matrix is extremely fine grained, and is composed mainly of microlites of feldspar and quartz, and perhaps some opal. The feldspar microlites are about 5 to 20 microns long, and consist of albite and potash feldspar in about equal amounts. These microlites compose about 40 to 50 percent of the specimens from the two beds. The quartz and opal are interstitial to the feldspar microlites and occur as tiny grains ranging in size from less than 0.2 micron (below the resolving power of the microscope) to about 3 microns across, though few are more than 1 micron across. Calcite and dolomite as grains and rhombs are conspicuously scattered through the matrix and prominent in short stringers of collapsed pumice fragments in both beds from this core. In essentially all specimens examined from both beds, prisms of apatite as much as 50 microns long are relatively prominent, and abundant apatite may be a distinguishing characteristic of these two tuff beds as well as of less conspicuous tuff beds in an interval extending upward for about 30 feet above B groove.

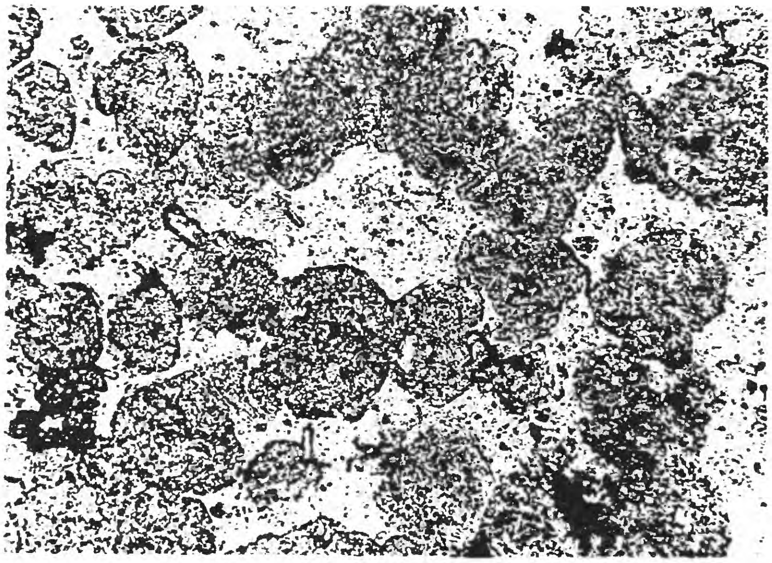

Figure 5.--Photomicrograph of a thin section of the curly bed from sec. 6, T. 4 S., R. 94 W. The extreme cloudiness of the analcite is due to included pyrite, calcite, opal, feldspar microlites, and cracking of the crystals. The matrix is composed of microlites of feldspar, opal, and microcrystalline quartz. The black grains are pyrite. Two prisms of apatite are visible. Plain light. X 150.

The Mahogany and false marker beds are essentially alike petrographically. Both typically contain less than 5 percent tiny phenocrysts in the altered matrix. In the outer part of the area these sparse phenocrysts are mainly crystal fragments of plagioclase and quartz, a few plates of biotite occurring in some specimens. In the Wasatch Development Co. Elizabeth 1 and the Shell Oil Co. Greeno 1 cores from the central part of the area only plagioclase, commonly with irregular overgrowths, and quartz are present as phenocrysts. Throughout the area the tiny phenocrysts are about 0.05 to 0.1 mm across. In the outer part of the area, both beds typically contain 55 to 65 percent analcite as subeuhedral to nearly perfect trapezohedrons that tend to be about the same size. These crystals also tend to be larger than those of the other beds, and some are as much as 0.4 mm in diameter; all are slightly to highly clouded by tiny inclusions, as described on page 13. The minerals interstitial to the trapezohedrons are mainly microcrystalline quartz and opal and microlites of albite; carbonate is important in some specimens. The grains of quartz and opal are 1 to 5 microns across, and the dominant quartz grains in some specimens are large enough to have a cherty appearance under the microscope. The microlites of feldspar, some of which are orthoclase, are about 10 to 50 microns long. The silica minerals and feldspar are present in approximately equal amounts, and together comprise about 25 to 35 percent of the specimens. The calcite and dolomite occur as grains and rhombs ranging from about 1 micron to as much as 0.5 mm across, and compose from as little as 1 to more than 15 percent of the specimens. Tiny pyrite grains and cubes compose 1 to 2 percent of the matrix. In the central part of the basin both beds are feldspathized, with the sparse tiny phenocrysts scattered through an extremely fine grained matrix composed mainly of feldspar microlites, opal, quartz, and carbonate. The feldspar microlites are essentially all albite, are about 5 to 40 microns long, and compose about 45 to 50 percent of the beds. The opal and quartz are interstitial to these microlites and are present as grains ranging in size from less than 0.2 micron (below the resolving power of the microscope) to about 2 microns across. These silica minerals form 30 to 40 percent of the beds. Grains and rhombs of calcite and dolomite are 1 to 50 microns across; they are scattered through the matrix, and constitute about 10 to 15 percent of the beds. Tiny grains and cubes of pyrite form about 1 to 3 percent of the beds. Figure 6 shows the Mahogany marker where it is analcitized; figure 7 shows this bed where it is feldspathized.

The wavy bed.--This is the most distinct of the altered tuff units in the Parachute Creek Member because of its common undulating streaks of collapsed pumice, for which it was named. These prominent dark-colored streaks, as much as 1-1/2 inches long, show under the microscope the collapsed tubes of original lapilli-size pumice fragments (figs. 8, 9). About 5 to 15 percent phenocrysts, ranging from about 0.05 to 0.5 mm in greatest dimension, are scattered through the altered matrix of specimens and consist mainly of biotite, plagioclase, and quartz, though a few phenocrysts of hornblende and pyroxene were noted in a specimen collected from near the base of the unit in sec. 16, T. 11 S.,

Figure 6.--Photomicrograph of a thin section of the Mahogany marker from a depth of 544 feet in the Bureau of Mines A core. The well-formed trapezohedrons have nearly clear rims, but their interiors are cracked and contain inclusions of opal, albite, carbonate, and pyrite. The matrix is mainly albite, microcrystalline quartz, and pyrite. Plain light. X 150.

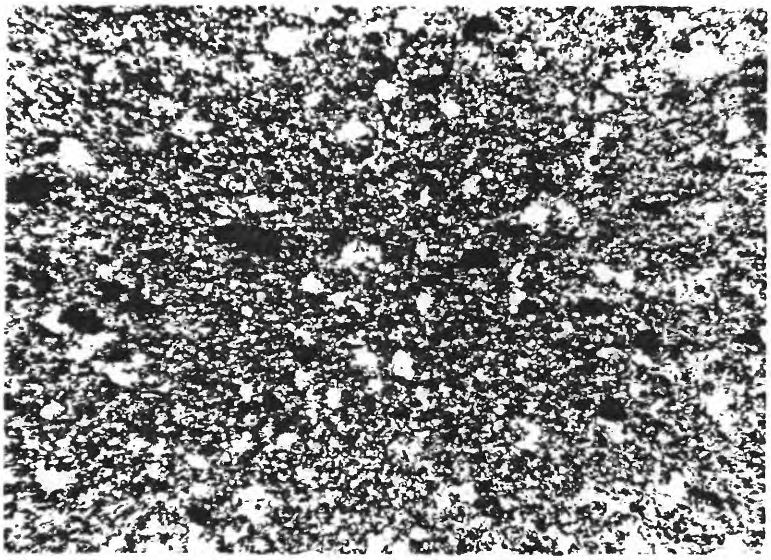

Figure 7.--Photomicrograph of a thin section of the Mahogany marker from a depth of 1,099 feet in the Shell Oil Co. Greeno 1 core. The fine-grained matrix is composed of microlites of albite, opal, quartz, and a little carbonate. The larger white grains are carbonate and highly albitized fragments of plagioclase. The black grains are pyrite. No analcite is present. Crossed nicols. X 150.

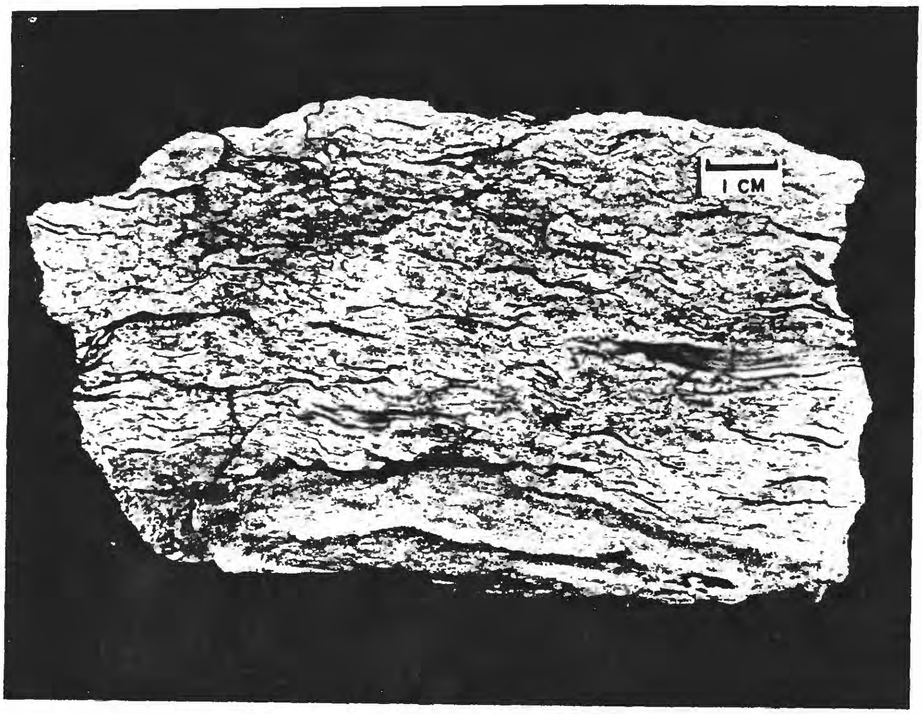

Figure 8.--Polished hand specimen of the wavy bed. The black contorted stringers are collapsed fragments of pumice.

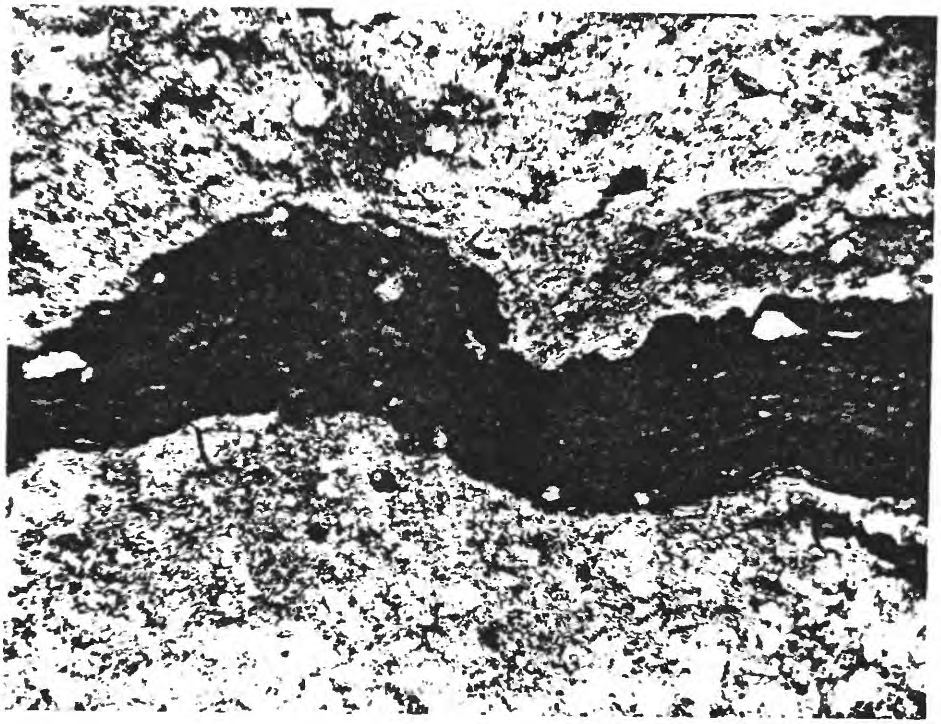

Figure 9.--Photomicrograph of a contorted stringer of collapsed pumice from the wavy bed showing the relict structure of the collapsed pumice tubes. The light-colored matrix is mainly anhedral to subhedral crystals of analcite with interstitial microlites of feldspar and grains of opal and quartz. Plain light. X 30.

R. 25 E., in eastern Utah, about 4 miles west of the Colorado State line. In the Shell Oil Co. Greeno 1 core, however, only plagioclase and quartz occur as phenocrysts; even relicts of biotite phenocrysts are absent here, the biotite apparently having disappeared completely during feldspathization of the bed at this locality near the center of the basin.

The altered matrix is dominantly analcite in all specimens examined except for one collected from the Shell Oil Co. Greeno 1 core. In the analcitized specimens of the unit the analcite forms about 45 to 55 percent of the rock. It occurs as anhedral grains to relatively well formed trapezohedrons ranging from about 0.025 to 0.4 mm across, though most are about 0.1 to 0.25 mm across. Some of the analcite is nearly clear except for reticulate cracking, and some is dusty, with tiny inclusions of pyrite, carbonate, and opal which are less than 1 to about 5 microns across. Microlites of feldspar, opal, microcrystalline quartz, carbonate, and pyrite are interstitial to the analcite. The feldspar microlites, 10 to 40 microns long, compose 10 to 20 percent of this interstitial aggregate, and X-ray diffractograms show that they consist of both albite and orthoclase, with albite more abundant. Opal and microcrystalline quartz form 10 to 25 percent of the interstitial aggregate; the quartz is dominant and in grains 1 to 5 microns across. Carbonate is highly variable in the matrix. One specimen collected in sec. 6, T. 4 S., R. 94 W., showed no carbonate, but this is exceptional. At the other extreme there is as much as 25 percent carbonate; the higher percentages are in specimens containing large amounts of the streaks of collapsed pumice which have been replaced largely by very fine grained carbonate and pyrite. The grains of carbonate are mainly calcite, as shown by X-ray analyses, and individual grains are 1 to 5 microns across. Some rhombs of dolomite are as much as 10 microns across. Pyrite is unimportant, ranging from a trace in some specimens to about 1 percent in others. It occurs mainly as grains and cubes less than 1 micron to about 10 microns across, but in some specimens it occurs as plates as much as 0.5 mm long which are believed to be pseudomorphic after marcasite.

In the one feldspathized specimen examined, which came from the Shell Oil Co. Greeno 1 core, the matrix contains about 45 percent microlites of feldspar, most of which are albite and 10 to 25 microns long, intermixed with about 40 percent quartz in grains ranging in size from less than 0.2 to 3 microns across. Dolomite as rhombs and calcite as irregular-shaped grains 2 to 10 microns across form most of the remainder of the matrix. These two minerals are mainly in streaks of collapsed pumice, but some are scattered through the fine-grained aggregate of feldspar and quartz. There is also about 1 percent pyrite as grains and cubes 5 to 20 microns across.

The upper zone of altered tuffs.--This zone of altered tuff beds is distinctive because closely spaced beds occupy a stratigraphic interval of 50 to 75 feet starting about 10 to 15 feet above the wavy bed (pls. 2, 3). Petrographically, the altered beds of the interval show the typical gradation from analcitized rocks around the edge of the area to feldspathized rocks in the center.

The beds contain about 5 to 25 percent phenocrysts as crystals and crystal fragments ranging from about 0.05 to 0.5 mm in greatest dimension. These phenocrysts are most abundant and varied in the U.S. Bureau of Mines A core at the southeast edge of the area; here all the beds contain tiny crystals or crystal fragments of plagioclase, quartz, and biotite, and essentially all contain some hornblende. Hornblende is not common elsewhere; it was found in only three beds as far west as the Gabbs Exploration Co. Mullins 2 core and in only one bed as far north as sec. 6, T. 4 S., R. 94 W., on upper Piceance Creek. Biotite prevails, however, except in the center of the basin, as far north as the Weber Oil Co. Juhan 1 core and as far west as the Gabbs Exploration Co. Elizabeth 1 core. One bed at a depth of 35 feet in the Juhan core contains more than 5 percent biotite--nearly as much as any of the beds in the southeastern part of the area. In the Wasatch Development Co. Elizabeth 1 and the Shell Oil Co. Greeno 1 cores near the center of the area, only the ubiquitous plagioclase and quartz occur as phenocrysts. The biotite has disappeared during the process of alteration in this part of the area, and the plagioclase phenocrysts in the Greeno 1 core are very highly albitized and flecked with tiny grains of calcite 1 to 10 microns across.

In the analcitized rocks, the crystals of this mineral are mainly ill formed, and are about 0.05 to 0.25 mm in diameter, though few reach the maximum of 0.25 mm. Opal and quartz interstitial to the analcite are variable in their proportions and in grain size. In some specimens opal is apparently important in grains that are less than 1 micron across, whereas in others there seems to be little opal, and tiny quartz grains are about 2 to 5 microns across. The feldspar microlites mixed with the opal and quartz are mainly albite as prisms that can be easily overlooked; in many specimens these prisms are as short as 5 microns, and few exceed 25 microns in length. Carbonate is highly variable in amount; in some specimens it is absent, or essentially so, but in others it constitutes as much as 15 percent of the rock. Both calcite and dolomite are represented, the calcite as irregular grains about 1 to 5 microns across and the dolomite in rhombs about 5 to 25 microns across. Pyrite occurs in trace amounts for the most part; in some specimens from cores near the margin of the area it is common as tiny blades about 0.025 to 0.5 mm long and is apparently pseudomorphic after marcasite.

Three of the beds are feldspathized in the Wasatch Development Co. Elizabeth 1 core, and all are feldspathized in the Shell Oil Co. Greeno 1 core (pl. 2). The matrix of these beds is dominantly feldspar and quartz. The feldspar is nearly all albite, in tiny prisms about 5 to 40 microns long which form about 35 to 45 percent of the specimens examined. The quartz grains are interstitial to the feldspar microlites, are less than 1 to about 3 microns across, and compose about 30 to 40 percent of the specimens. Opal is absent, or essentially so. Dolomite is more abundant than calcite in all the specimens examined, but grains and tiny rhombs of these minerals, about 1 to 50 microns across, compose about 5 to 15 percent of the specimens. Pyrite is variable in amount, comprising from a trace to about 2 percent of the specimens, and occurs as grains and cubes about 2 microns to 0.25 mm across. Dawsonite ($Na\ Al(OH)_2\ CO_3$) was noted in two slides as tiny prisms about 0.05 to 0.5 mm long.

X-ray analyses showed negligible potash feldspar in all but one specimen from this zone of altered ash falls; therefore essentially all the glassy ash probably was dacitic originally.

The white bed.--The bed of altered white tuff mentioned on page 12 contains about 25 percent phenocrysts of plagioclase in a matrix of irregular-shaped to subeuhedral trapezohedrons of analcite. The interstices between the analcite grains and crystals are filled mainly by albite microlites about 10 to 25 microns long, opal, grains of quartz about 1 to 3 microns across, and some pyrite. Apatite is conspicuous as an accessory. This bed may be important, as it is believed to represent the last ash fall in the Parachute Creek Member in the area. As little or no potash feldspar is in the altered specimens of the rock, the bed is believed to have been a dacite tuff originally.

THE WATER-WASHED TUFFACEOUS ROCKS

Rocks composed of altered, water-washed tuff appear in the upper part of the Parachute Creek Member and compose most of the lower part of the Evacuation Creek Member. Two tongues of these rocks are in the Parachute Creek Member in the Shell Oil Co. Greeno 1 and in the Wasatch Development Co. Elizabeth 1 cores. These two tongues, pinching out to the south, are referred to as tongues 1 and 2 on plate 2. A similar tongue, apparently composed of such rocks but occurring somewhat lower in the stratigraphic section, has been seen at the surface exposures in sec. 13, T. 1 N., R. 97 W. This third tongue pinches out southward before reaching the Shell Greeno well. At the southeast edge of the basin, similar rocks which must be laterally equivalent to the Evacuation Creek Member to the north and toward the center of the basin are in the upper part of the Parachute Creek Member in the U.S. Bureau of Mines A core. Three thin stratigraphic intervals composed of rocks of this type occur in this core between depths of 110 and 160 feet (pl. 2). The basal 7 to 23 feet of the Evacuation Creek Member, below the first thin marlstone bed, also is composed of such rocks, as evidenced by the seven cores studied. In addition, the lower 400-600 feet of the Evacuation Creek, exclusive of interbedded thin units of marlstone, is apparently all or essentially all composed of altered, water-washed, tuffaceous material.

These rocks are light gray to gray and weather tan to brown. They have a silty to fine sandy appearance in the field, and ash-fall bedding is absent from thick stratigraphic intervals which they occupy. Instead, the bedding is irregular to lenticular, individual beds ranging in thickness from 0 to about 20 feet.

Thin sections of these rocks contain crystal fragments of plagioclase, sanidine, and quartz, plates of biotite, and rare hornblende (fig. 10). The crystal fragments show little or no evidence of abrasion, and compose about 10 to 20 percent of the rocks. They range in size from about 0.05 to about 0.25 mm across or in greatest dimension, and are scattered or "floating" in an altered matrix. The plagioclase fragments are finely twinned like those in the altered ash-fall beds and are typical of finely twinned plagioclase of volcanic rocks. Most or all of these fragments are slightly to highly albitized, and some contain grains of calcite about 1 to 3 microns across, but unaltered portions are sodic andesine. The sanidine fragments from two specimens were approximately $Or_{60}Ab_{40}$. Fragments of this mineral are unaltered. The biotite plates are highly pleochroic, with α=pale brownish yellow and β and γ pale greenish tan to pale clove brown. The rare hornblende is the green variety. Traces of foreign microcline and less rare plates of foreign muscovite have been noted in a few slides.

The highly altered matrix of these rocks is composed mainly of albite, orthoclase, quartz, and opal, varying amounts of analcite, calcite, and dolomite, and very small amounts of pyrite. The albite and orthoclase are present as microlites ranging in length from about 10 to 40 microns. The albite is nearly pure, as indicated by X-ray analyses, and generally exceeds the orthoclase in amount. The grains of quartz and opal are less than 1 to about 3 microns across and are interstitial to the feldspar microlites. Analcite is absent from some of these rocks in the central part of the area, but it commonly forms about 5 to 15 percent of the matrix in the outer part, where it occurs as clear subrounded grains about 10 microns across; it, also, is interstitial to the feldspar. Calcite and dolomite compose about 5 to 15 percent of the matrix; the calcite is in irregular grains about 2 to 20 microns across, and the dolomite occurs as rhombs about 5 to 60 microns across. Pyrite, generally in part altered to iron oxide, forms about 1 to 2 percent. It is present as grains, aggregates of grains, and cubes; individual grains are as small as 10 microns, and aggregates of grains are as much as 100 microns across; the sparse cubes are about 10 to 25 microns across. Apatite and zircon are accessories, with some slender prisms of apatite as much as 50 microns long.

This water-washed tuffaceous debris must have been deposited as sludge by waters heavily laden with debris if one is to explain the "floating" crystal fragments in what probably was a matrix of fine glass at the time of deposition. The stratigraphic distribution indicates that the source of the debris was to the north of the area.

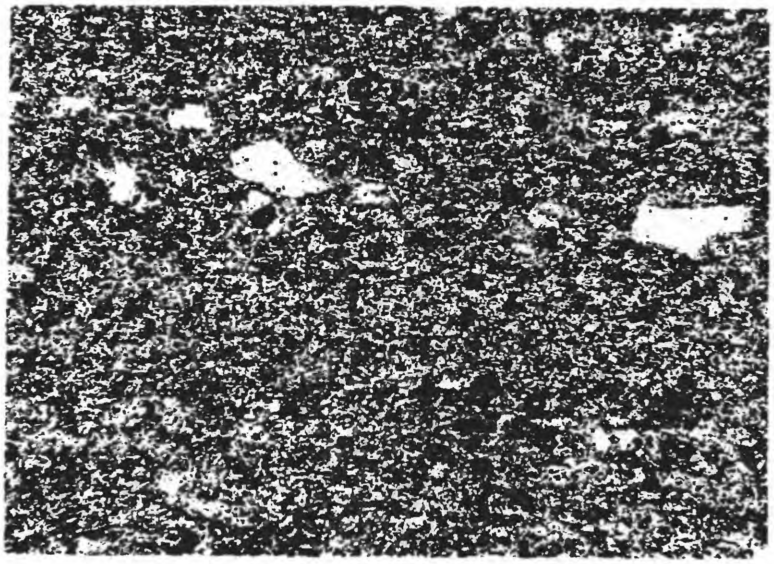

Figure 10.--Photomicrograph of a thin section of water-washed tuff from the basal few feet of the Evacuation Creek Member of the Green River Formation in sec. 1, T. 4 S., R. 95 W. The white fragments are feldspar. The matrix is microlites of feldspar with interstitial grains of opal and quartz and some subrounded crystals of analcite. Crossed nicols. X 150.

Chemical analysis and approximate mode of a specimen of the water-washed tuff

[Specimen collected by John R. Donnell from the basal few feet of the Evacuation Creek Member in a core taken by the Pure Oil Co. in sec. 36, T. 7 S., R. 94 W. Analysis by U.S. Geological Survey]

Analysis		Approximate mode	
SiO_2----------	64.94	Analcite-----------------------	20
Al_2O_3---------	14.22	Chalcedony, quartz, and opal---	30
Fe_2O_3---------	.17	Andesine, sanidine, albite, and	
FeO-----------	1.37	orthoclase-------------------	35
MgO-----------	1.12	Biotite------------------------	6
CaO-----------	2.41	Calcite and dolomite-----------	8
Na_2O----------	4.10	Pyrite and iron oxide----------	1
K_2O-----------	4.36	Apatite------------------------	Trace
H_2O^+----------	4.07		100
H_2O^-----------	.14		
TiO_2----------	.22		
P_2O_5----------	.13		
MnO-----------	.05		
CO_2-----------	2.71		
Cl------------	.01		
F-------------	.03		
	100.05		

PETROLOGY

The most interesting result of the study is the recognition of a general transition from analcitization of the altered ash-fall beds near the margin of the basin to feldspathization of these beds at the center. This general transition is clearly shown on plates 2 and 3. The only exceptions to the generalization are several feldspathized beds in the lower 250 feet of the Weber Oil Co. Juhan 1 core at the northeastern margin of the basin and one analcitized bed in the Shell Oil Co. Greeno 1 core at the center. There is a similar trend in the case of the water-washed tuffaceous rocks. Although feldspathization is dominant in these rocks, even at the basin margin, some specimens do contain as much as 20 percent analcite in the marginal area; in rocks at the center of the basin, also, analcite is rare.

Field observations

A concept of the origin of the alteration and transition is considered first from the standpoint of field observations. Bradley (1929, p. 3-5) presented evidence that the analcite of the formation probably formed at a temperature below 30°C and before it was buried to a depth of 100 feet. His evidence consisted of the observations that intimately associated organic matter of the oil shale of the Green River Formation showed no evidence of thermal alteration and that the analcite crystals (some of which show slight distortion) showed no evidence that they formed under a load of as much as 100 feet. The transitional alteration to feldspathization in the area was unknown at that time, but the organic matter associated with this alteration shows no evidence of thermal alteration. Coombs (1954) studied a 28,000-foot section of Triassic graywacke with interbedded tuff which is mainly or entirely of marine deposition. He believed (1954, p. 79) that the analcitized tuffs in the section could have formed from volcanic glass at atmospheric temperatures but stated that whether normal sea water at these temperatures affected the change was inconclusive. He stated further (1954, p. 95) that "perhaps all of the authigenic albite of the Upper Triassic replaces earlier formed analcime," but he apparently believed (1954, p. 95) that in general the destruction of analcite and the increase in albite with depth was due to thermal metamorphism.

Recently, Gulbrandsen and Cressman (1960) have studied the alteration of a 5-foot tuff bed in the Jurassic Twin Creek Limestone in Idaho and Wyoming. This altered tuff, deposited in marine waters, consists mainly of fine-grained analcite and quartz at three localities; these writers described the altered bed as an "analcime chert." At a fourth locality the bed has altered mainly to fine-grained albite and quartz. They (Gulbrandsen and Cressman, 1960, p. 463) believed that the tuff bed first altered to the so-called analcime chert and that later "the analcime apparently converted entirely to albite at one locality but only in small amount at most of the other localities that were sampled. This difference suggests that the tuff bed when deeply buried was not everywhere at the same temperature, or possibly the rate of transition was different due to unknown factors. It could be attributed, also, to primary differences in composition if there are two tuff beds rather than the single continuous one considered throughout this study."

Laboratory investigations

Most of the laboratory work on the systems $K_2O-Al_2O_3-SiO_2-H_2O$ and $Na_2O-Al_2O_3-SiO_2-H_2O$ has involved the use of colloidal gels as the starting substance. This seems to be an important factor in the alteration problem at hand, and therefore will be discussed.

In 1952 Barrer and White (1952) described in detail the growth of crystals from gels of the composition $Na_2O-Al_2O_3-SiO_2-H_2O$, the gels being made alkaline by the addition of NaOH. Crystals of analcite were grown in short runs (apparently a matter of days at the most) at a temperature as low as 150°C and a pH of 9.0, and both analcite and albite crystals were grown in the same run at a temperature of 330°C where the pH was as low as 8.0. Sand, Roy, and Osborn (1957), working specifically on the stability relations in the same system, found that analcite slowly disappeared and albite slowly formed at 290°C, but they suggested that albite might be stable at much lower temperatures. Pressure had little effect on the reaction. More recently, Hemly has studied the systems $K_2O-Al_2O_3-SiO_2-H_2O$ (1959) and $Na_2O-Al_2O_3-SiO_2-H_2O$ and $K_2O-Al_2O_3-SiO_2-H_2O$ (1961). He has made the very important observation that the alkali ion/hydrogen ion ratio has a very significant effect on hydrolysis reactions and mineral equilibria in these systems. In oral communication (1961) to the writer he stated that thus a higher pH would cause a higher silica activity and therefore favor the formation of albite over analcite.

Genesis of the analcite and feldspar

It is beyond the scope of this paper to discuss the origin of the alkaline and otherwise peculiar waters of the Green River lakes which presumably were largely responsible for the well-known suite of unusual authigenic minerals in the Green River Formation (Milton, 1957; Milton and others, 1960). However, the alkaline water of the Piceance Creek Basin portion of the lake and its entrapment in the consolidating rocks are believed responsible for the alteration of the tuffaceous rocks.

The water entering the lake probably had drained volcanic terranes, and through the leaching of these terranes had acquired appreciable sodium. Even the marginal water was quite sodic at times, and, owing to the equal evaporation rate from the lake surface as a whole, the sodium content must have progressively increased toward the center. The marginal alkalinity of the original water is borne out by molds of so-called "evaporite" minerals (probably nahcolite) at surface exposures, by a 1-inch bed of nahcolite that has been noted in the formation in the Savage Oil Shale Co. 1 Camp core, and by another similar bed in the

U.S. Bureau of Mines oil-shale mine near Rifle, Colo. In the center of the basin, beds of nahcolite as much as 1 foot thick are not uncommon, and disseminated crystals of dawsonite (Na $Al(Co_3)(OH)_2$) are fairly common, some occurring in albitized tuff beds. This mineralogical evidence indicates a progressive change in the alkalinity of the water toward the lake's center. This change in alkalinity, possibly coupled with a slight temperature change in the subsiding basin, is believed to have been responsible for the general transition from analcitization to feldspathization toward the center of the basin.

The details of the breakdown of the complex alumino-silicate glass of the volcanic ash are unknown, but it is believed to have occurred during diagenesis, as documented by a small sill-like injection of analcitized tuff collected in sec. 14, T. 1 N., R. 97 W., in Rio Blanco County, Colo. This sill-like mass, about 1 foot long, was injected into enclosing oil shale by a thin "dike" feeder about 1 inch thick which extended downward for a few inches from a bed of analcitized tuff about 2 inches thick. Intricacies of the intrusion indicate that the enclosing oil shale was still mushy, and the crystals of analcite show no evidence of shearing during the intrusion. The analcite crystallized after its injection.

In order to explain the fluidity and subsequent crystallization of the sill-like injection it is necessary to assume that the tuff beds passed through a fluid state during diagenesis. As the high-silica glass of the felsic ash could not have dissolved to form a true solution, the fluid state must have been a colloidal gel.

Presumably, the authigenic analcite and feldspar of the altered tuffaceous rocks formed most readily under natural conditions, just as it does in the laboratory, from a gel (see p. 35), the feldspar forming at a higher alkali/H^+ ratio, with consequently higher silica activity. The writer would like to point out, however, that there may not have been sufficient water entrapped with the original glass for a gel to form, but, as silicate sols are lyophyllic, additional water could readily have been drawn across the boundaries of the enclosing undehydrated oil shale and carbonate beds and into fine ash as the sols formed. Evidence for this transfer is presented by the extraneous carbonate in the matrix of the altered tuffaceous rocks as well as bulges along the contacts of some of the altered beds, and the form of such features as the small sill-like intrusion cited above.

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